

Modified Electrical Model of MJSC for Concentrated Photovoltaic under Changing Environmental Conditions

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Abstract- This paper presents a mathematical model for a Multi-Junction Solar Cell (MJSC) that achieves higher efficiency and improved temperature characteristics compared to conventional SCs. The model is based on the single (SD), double (DD) and triple diode (TD) equivalent circuit models used to represent SCs. An additional term representing avalanche breakdown voltage was incorporated into the model. The electrical parameters of the MJSC were studied over a range of concentration ratios (C_r) from 20X to 1000X, direct normal irradiance intensities from 200 W/m² to 1000 W/m², and cell temperatures from 15°C to 100°C. The parameters studied included open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), maximum power (P_{max}), fill factor (FF), and efficiency (η). The results showed that all electrical parameters increased with radiation up to a 500X, after which the FF started to decrease reducing cell efficiency. From 500X to 1000X concentration, V_{oc} , I_{sc} , and η increased from 3.1V to 3.2003V, 6.8A to 13.6A, and 37% to 37.5%, respectively. Higher cell temperatures reduced performance as V_{oc} decreases linearly with temperature. The temperature coefficients of V_{oc} and I_{sc} were determined to be around -5.4mV/°C and 4mA/°C respectively at 500X concentration. Total efficiency decreased at a rate of approximately 0.03%/°C as temperature increased. The model demonstrated that the MJSC design achieves higher efficiency than conventional cells over a wide range of operating conditions due to improvements in voltage, current and temperature characteristics.

Keywords Multi-junction PV Cells, Concentration, Mathematical model, Electrical properties, Electrical Efficiency, Solar energy.

1. Introduction

More than 80% of the world's energy is currently obtained from finite resources like natural gas, coal, and oil. Continued reliance on these sources risks their depletion or vanishing within a short time frame. While traditional electricity generation from these resources is inexpensive and convenient, it results in massive greenhouse gas emissions such as CO₂ that contribute to global warming [1],[2]. To avoid this serious situation, green energy resources (e.g. solar, tidal, wind, geothermal,...) that are environmentally friendly, independent, cost-effective, reduce energy bills, and have low maintenance costs need to be developed and more

widely adopted[3]. Photovoltaic (PV) cells convert sunlight directly into electrical energy via the PV effect. However, conventional PV performance remains unsatisfactory. Factors like cloud cover, temperature variation throughout the year, and surrounding dirt, dust, trees, and buildings decrease PV output and efficiency [4].

One of the different PV cells is the MJSCs based on III–V and II–VI semiconductors. MJSCs are more efficient PV cell technology than conventional single-junction ones [5] and possess less deterioration than silicon SCs. In [6], Renno et al. discussed detailed characteristics and made comparisons between first, second, and third-generation PV

technologies. Concentrating PV Systems (CPVs) confidently offer a solution that combines low-cost optical concentrators and concentration SCs, providing a number of impressive financial benefits. Concentrating optics are reflective mirrors or refractive lenses that are very cheap materials that can concentrate the sunlight onto a small area of a semiconductor SC and consequently reduces the SC material cost [7,8]. The ratio of the SR that strikes the optical concentrator's surface to the SR that the MJSCs receive is the CPV unit's concentration ratio C_r . When it comes to PV cell technology, MJSCs have outperformed all other methods in terms of efficiency. For example, the maximum independently verified efficiencies for MJSCs increased from 29.1% in 2018 to 47.1% in 2020, the most recent confirmed efficiency record [9]. Practically MJSCs provide conversion efficiencies upwards of 46% (AM1.5d, 508 suns) [10]. Since commercial MJSC has a FF >0.8, it dominates the high-concentrator market, while single cells are usually only used in low-concentration applications [11].

A definition must be cleared, Lattice refers to the organized pattern of atoms in a semiconductor material. When two different crystalline materials are joined together, if they have the same arrangements of atoms and spacing between them it named as lattice matched junction, else it creates strain at the interface where they meet. This is known as lattice mis-matched junction[12].

Numerous studies have been conducted to simulate and analyze the performance of MJSC integrated into concentrating systems with different C_r values. Several recent research models connected n number of equivalent single/double diode cell in series. In [13] a model based on two sub-cells equivalent lattice matched Triple Junction SCs (TJSC) with a SD was built to predict the maximum power point of a SC at (25 °C, one sun concentration and variable SR). [14] built a CPV module based on an InGaP/InGaAs/Ge TJSC with excellent efficiency. By using SR and cell temperature as input parameters, the model generates I-V and P-V characteristics under a variety of situations and also accounts for the effect that temperature variations have on the cell characteristics. In [15] modeling of MJSC to improve the conversion efficiency shows that the combination InGaP/GaAs/Ge offered the best performance tandem cell as it could deliver 3-times power than conventional cells. In [16] A. Hussain et al. established one model for a single junction and another one for MJSC to demonstrate and analyze different environmental conditions that affect the SCs, such as temperature and SR. All these references model the conversion efficiency using a SD Musing model using Matlab/Simulink environment. Modeling the conversion efficiency using a double-diode MJSC model was performed in [17][18].

At a C_r of 576X, H. Lv et al. in [19] studied the influence of cell temperature on its electrical characteristics and found that as temperature rose from 275° K to 375° K ,

the module's efficiency, P_{max} , and V_{oc} all dropped. These values dropped from 28.5% to 21.5%, 85 W to 62 W, and 108 V to 94 V, respectively. The performance of MJSC under STC was studied in [20] and found that open-circuit voltage decreased with increasing short-circuit current. Authors of [21] provide a model for simulating CPV-hydrogen systems and go over the techno-economic analysis and multi-objective optimization approach for the system's independent functioning.

J. Parravicini et al. compare the Si and MJSC SC performance in [22]. The results show that the MJSC module is approximately twice as effective as the Si SC module, and in outdoor settings, the MJSC module outperformed the Si SC. The concentrator was operating with a thermal efficiency of 51.3% and an electrical efficiency of 10.2%, according to the testing data, resulting in an overall system efficiency of up to 61.5%.

A specific configuration of HCPV system is considered, and the experimental analysis of a system's electrical properties degradation was performed in [6]. They found that the module power was reduced by 45.8% after 500 hours of working in the identical outside circumstances. In [23] LCPV experimental prototypes were designed, built, and evaluated concerning optimization of the optical, electrical, the thermal subsystems and overall performance.

Modeling methodologies for CPV systems can generally be categorized into four main approaches[24]. Simple models like the Shockley-Queisser model provide fast simulations but are too idealized to capture real-world effects. Most empirical models are fast to run but are only applicable for materials like Silicon or III-V semiconductors near room temperature.

Temperature dependent models and those based on detailed material properties can provide more accurate simulations but require significant initial effort to develop the various empirical relations. They are also dependent on the accuracy of the underlying empirical models.

Quantum mechanical based approaches can in principle offer highly consistent internal results given sufficient expertise and resources. However, developing these models typically requires extensive work and computational resources.

When a CPV panel experiences partial shading, the shaded CPV cells may not generate electricity and could even consume power produced by other illuminated cells. This phenomenon, known as reverse bias, causes the cell to exhibit a negative voltage at its terminals. As a result, it operates in the second quadrant of the voltage-current curve with negative voltage and positive current. Neither the simple Shockley-Queisser model nor SDM or DDM can accurately capture this reverse bias effect occurring at the individual cell level under partial shading conditions, so Bishop model was chosen to address this avalanche mechanism.

This paper uses MATLAB/Simulink, high-level software to simulate numerical models, build algorithms, and analyze the results [24], to study the CPV SC performance and organized as follows: Introduction is in section 1, including a brief review in MJSC modelling ways and studies done on CPV cell electrical performance, theory and modeling of MJSC using MATLAB/Simulink is in section 2,

analysis of SCs' electrical performance under variable environmental conditions done with different C_r is in section 3. Finally, section 4 provides an overall conclusion about the work that has been performed.

The main contributions in this paper are:

1. A detailed basic SD-MJSC model including the effect of wind speed in cell temperature and electrical parameters temperature coefficients.
2. An extended model for double and triple diode MJSC with breakdown voltage representing cell reverse bias, partial shading, and junction mismatch effect.
3. Study the effect of SR, temperature, and C_r variation on cell electrical coefficients.

2. Mathematical modelling of MJSC

2.1 Basic model

MJSC can be defined as a SC having two or more single-junction semiconductors stacked on top of one another with diminishing bandgaps from top to bottom. An advantage of this structure is the minimization of losses caused by the transmission of low-energy photons and the thermalization of hot carriers and which enables the absorption of a wider range of solar spectrum photons [25] means more generated current, power, and efficiency. In the present work, a detailed current mismatched triple-junction SD SC is adapted to develop a numerical model to express the I-V curve of a CPV cell at different SR intensities, cell temperatures, and concentrations ratios. This model extended to include double (DD) and triple diode (TD) model for more accuracy. The choice of wavelength intervals at which the sun spectrum should be split by the MJSC, which establishes the current density and voltages of each subcell, is what determines the best bandgap combinations. [10]. In the case of a TJSC, Figure 1 illustrates the broad photosensitivity concept employing MJSC. The SC facing the sun, GaInP, has the biggest band gap among the SCs stacked on top of one another, with a band gap E_g of (1.8-1.9 eV). Through the higher SC, which absorbs all photons at and above its bandgap energy, the less energetic photons are transmitted to the SCs below. All transmitted photons with energies equal to or greater than their band gap energy are absorbed by the next SC in the stack, which in this instance is the middle InGaAs SC with an E_g of 1.41 eV. The remaining photons are sent down the stack. (in this case, to the Ge bottom SC with an E_g of 0.67 eV).

Depending on the field of application and referring to Fig. 1, MJSCs are classified using various reference spectra. The reference spectrum (AM0) with a total irradiance of 1367 W/m² is used for space applications. Applications for terrestrial concentrators use the 1000 W/m² AM1.5d spectrum, which is limited to absorbing direct normal illumination (DNI) [26], and all diffused irradiance is lost as dissipated heat. Figure 2 depicts the top, middle, and bottom sub-cells of the equivalent circuit of InGaP/InGaAs/Ge in the

case of a TJSC. Each cell does as a current source and all cells are connected in series, hence the net cell-generated voltage is as in Eq.1 and the resulting current is limited by the smallest current source.

$$V_c = \sum_{i=1}^3 V_i \quad (1)$$

$$I_c = I_{phi} - I_{Di} - I_{shi} \quad (2)$$

Where $i = 1, 2, 3$ represents the sub-cell layer number. V_c , V_i , I_c , I_{phi} , I_{Di} , I_{shi} are the net cell voltage(V), local sub-cell voltage (V), net cell current (A), photo-generated current, diode current (A), and shunt resistance current (A), respectively.

The photo-generated current as a function of SR, concentration, and cell temperature can be calculated as in the following equation [27]:

$$I_{phi} = \frac{rad}{1000} * C_r * [I_{sc_i} + a_i(T_c - T_{ref})] \quad (3)$$

Where, rad , C_r , I_{sc} , a_i , T_c , and T_{ref} are SR (W/m²), concentration, and short-circuit current (A), current temperature coefficient (A/°K), cell temperature(°K), and reference temperature (298°K), respectively.

The equation for the diode's current as a function of the voltage that is put across it is known as the diode current equation is expressed mathematically as [14]

$$I_{Di} = I_{oi} \left[\exp \left(\frac{qV_{Di}}{n_i K_B T_c} \right) - 1 \right] \quad (4)$$

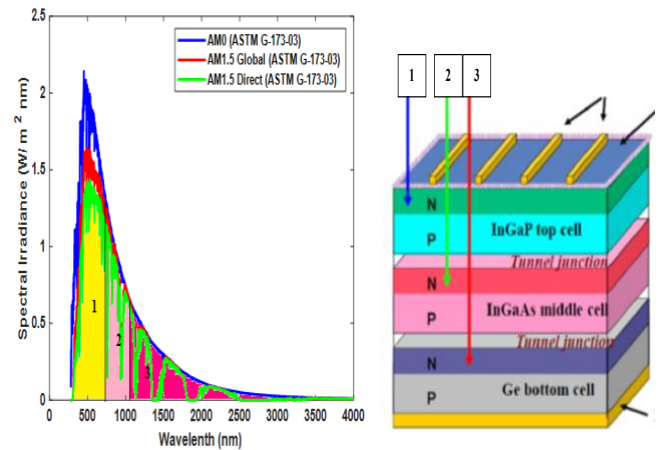


Fig. 1 photo response by MJSC, and Spectral irradiance distribution solar spectrum ASTM G-173-03 (AM 0, AM1.5).

Reverse saturation current is given by [28]:

$$I_{oi} = K_i \times T_c^{(3+\gamma_i/2)} \left[\exp \left(-\frac{qE_{gi}}{n_i K_B T_c} \right) \right] \quad (5)$$

$$V_{Di} = V_i + I_c \times R_{si} \quad (6)$$

Where, I_{Di} , I_{oi} , q , n_i , K_B , V_{Di} , are current pass through the diode (A), diode dark saturation current (A), the diode leakage current density in the absence of light, electron

charge ($1.602176634 \times 10^{-19}$ C), diode ideality factor, Boltzmann constant ($1.38064852 \times 10^{-23}$ m² kg s⁻² K⁻¹), respectively. K_i , γ_i are constants related to the fabrication process, and their values are governed by the diffusion and recombination of electrons and holes [25]. V_i and R_{si} are the cell output voltage (V), and series resistance of each sub-cell (Ω), respectively.

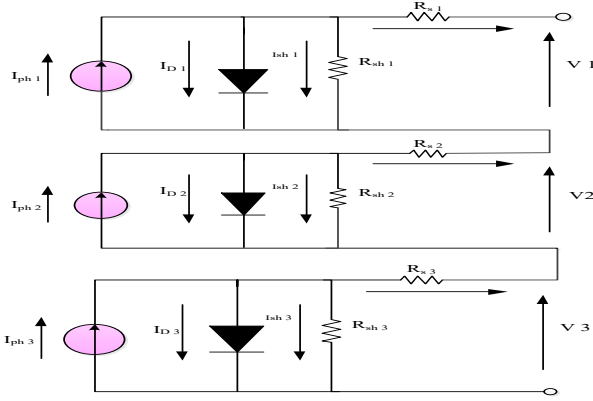


Fig. 2. Equivalent circuit of SD- TJSC.

Semiconductors' bandgap energy tends to decrease as the temperature increases. This is because the inter-distance among material atoms increases as the amplitude of vibration increases due to an increase in thermal energy. This effect of the material is quantified by the linear expansion coefficient. Inter-atomic distance increases and electrons have a less potential barrier, which in turn reduces the size of the band gap. The variations of energy bandgaps with temperature are as [29]:

$$E_{gi}(T_c) = E_{gi}(0) - \frac{\alpha_i T_c^2}{T_c + \beta_i} \quad (7)$$

$E_{gi}(0)$, β_i , is the bandgap of each sub-cell at zero kelvin, material constant, respectively. Cell temperature affected by wind value, no matter it's the direction, the wind has a cooling effect on the cell temperature [14,15]:

$$T_c = T_{amb} + rad * e^{-3.473 - 0.0594 w_s} \quad (8)$$

Where, T_{amb} , and w_s are ambient temperature ($^{\circ}$ K), and wind speed (m/s²), respectively. Taking in account R_s is very small and its effect can be neglected, I_{sc} is the highest current gained from the SC, while I_0 is a very low number so, cell voltage at concentrated light is calculated as follows:

$$V_{oc}(C_r) = \frac{K_B T_c}{q} (n_1 \ln \left[\frac{C I_{sc}}{I_{01}} \right] + n_2 \ln \left[\frac{C I_{sc}}{I_{02}} \right] + n_3 \ln \left[\frac{C I_{sc}}{I_{03}} \right])$$

$$V_{oc}(C_r) = \frac{K_B T_c}{q} \sum_{i=1}^3 (n_i \ln \left[\frac{I_{sc}}{I_{0i}} \right] + \ln(C))$$

(10) I_{sc} and V_{oc} of MJCS may be determined at any cell temperature and concentration, By utilizing the corresponding temperature coefficients and the cell performance change versus concentration at 25 $^{\circ}$ C.

$$V_{oc}(T_c, C_r) = [V_{oc}(\text{at } 25^{\circ}\text{C})]_c + (T_c - 25) \left[\frac{dV_{oc}}{dT_c} \right]_c \quad (11)$$

$$I_{sc}(T_c, C_r) = [I_{sc}(\text{at } 25^{\circ}\text{C})]_c + (T_c - 25) \left[\frac{dI_{sc}}{dT_c} \right]_c \quad (12)$$

FF measures the quality of the SC and mainly depends on the cell's R_s and R_{sh} [32], increasing the R_{sh} and/or decreasing the R_s results in a higher FF, makes the cell's output power nearer to its theoretical maximum and so has greater efficiency [33]. It can be calculated as follows:

$$FF = \frac{I_{mpp} V_{mpp}}{I_{sc} V_{oc}} \quad (13)$$

Cell efficiency fluctuates with concentration and temperature as [18, 19]:

$$\eta_{MJSC} = \frac{1}{P_{in}} \sum_{i=1}^3 (V_{oc} I_{sc} FF)_i \cdot 100 \quad (14)$$

Where, I_{mpp} , V_{mpp} , are cell maximum current (A) and voltage (V), respectively. P_{in} is the incident power on the SC (W).

2.2 Bishop Model:

At non-uniform illumination, partial shading, and junction mis match, the SC may operate at negative voltage. This effect known as the avalanche breakdown effect symbolized as a dependent current source series with R_{sh} .

$$Av(v) = 1 + \omega \left(1 - \frac{V_c + I_c R_s}{V_{br}} \right)^{-m} \quad (16)$$

Where, ω , m , V_{br} are a constant representing the ohmic fraction of the current related to the avalanche breakdown, the avalanche breakdown exponent, and the junction breakdown voltage, respectively.

For more accuracy, equation 2 rewrote to express DD and TD SC model represented in Fig.3.

$$I_C = I_{ph} - I_{O1} \left[\exp \left(\frac{qV_{D1}}{n_i K_B T_C} \right) - 1 \right] - I_{O2} \left[\exp \left(\frac{qV_{D2}}{n_i K_B T_C} \right) - 1 \right] - \frac{V_{Di}}{R_{shi}} \left[1 + \omega \left(1 - \frac{V_C + I_C R_s}{V_{br}} \right)^{-m} \right] \quad (17)$$

$$I_C = I_{ph} - I_{O1} \left[\exp \left(\frac{qV_{D1}}{n_i K_B T_C} \right) - 1 \right] - I_{O2} \left[\exp \left(\frac{qV_{D2}}{n_i K_B T_C} \right) - 1 \right] - I_{O3} \left[\exp \left(\frac{qV_{D3}}{n_i K_B T_C} \right) - 1 \right] - \frac{V_{Di}}{R_{shi}} \left[1 + \omega \left(1 - \frac{V_C + I_C R_s}{V_{br}} \right)^{-m} \right] \quad (18)$$

3. Results and Discussion

3.1 Model Validation

According to previously mentioned equations, a TJSC InGaP/InGaAs/ Ge with parameters in table 1 was modeled using Matlab m.file. The cell performance can be plotted in terms of generated voltage, current, power, FF, and efficiency. Consequently, by contrasting the outcomes with indoor experimental data from manufacturers, the model is validated under 900W/m² SR, 555X, 25°C air temperature, and AM1.5 d solar spectrum as in fig.4. Figure 5.a gives the I-V curve of each layer and the net I-V curve. Resulting in 6.83A cell current and 3.1V cell open-circuit voltage. The modeled SC is lattice-mismatched, so the current of each cell is different which increases the current loss and consequently, decreases overall cell efficiency. Figure 5.b is the power-voltage characteristic curve clearly showing cell 18.7 W maximum power, 0.88 FF, and 37.53% efficiency.

3.2 Solar Radiation and Temperature Effect on MJSC

Figure 6 depicts the properties of the SC at different SR and temperature levels. I-V curves illustrating the impact of changing SR from 200 W/m² to 1000 W/m² at a constant temperature of 25°C and 500X concentration are shown in Figure 6(a). According to the results, when radiation increases from 200 W/m² to 1000 W/m², V_{oc} increases by 0.04%, I_{sc} increases by 4%, and cell efficiency increases by 0.02%. Low series resistance and high shunt resistance contribute to maintaining a largely constant FF.

Figure 6(b) shows the change in open-circuit voltage with temperature for the MJSC. V_{oc} decreases with temperature at a rate of 5mV/°C. This reduction occurs as temperature increase effectively lowers the bandgap and increases the ability of bound electrons to break free from the valence band, thus decreasing E_g . Results also show that short-circuit current increases slightly with temperature at a rate of 4mA/°C. This is because I_{sc} is directly proportional to the number, mobility, generation rate, and diffusion length of charge carriers. The generation rate of charge carriers increases with cell temperature, thereby increasing I_{sc} .

On the other hand, the FF of the MJSC decreases slightly with increasing temperatures. As a result, efficiency decreases by 0.03%/°C as temperature rises from 15°C to 100°C. In summary, the key electrical parameters are affected by variations in SR intensity and temperature.

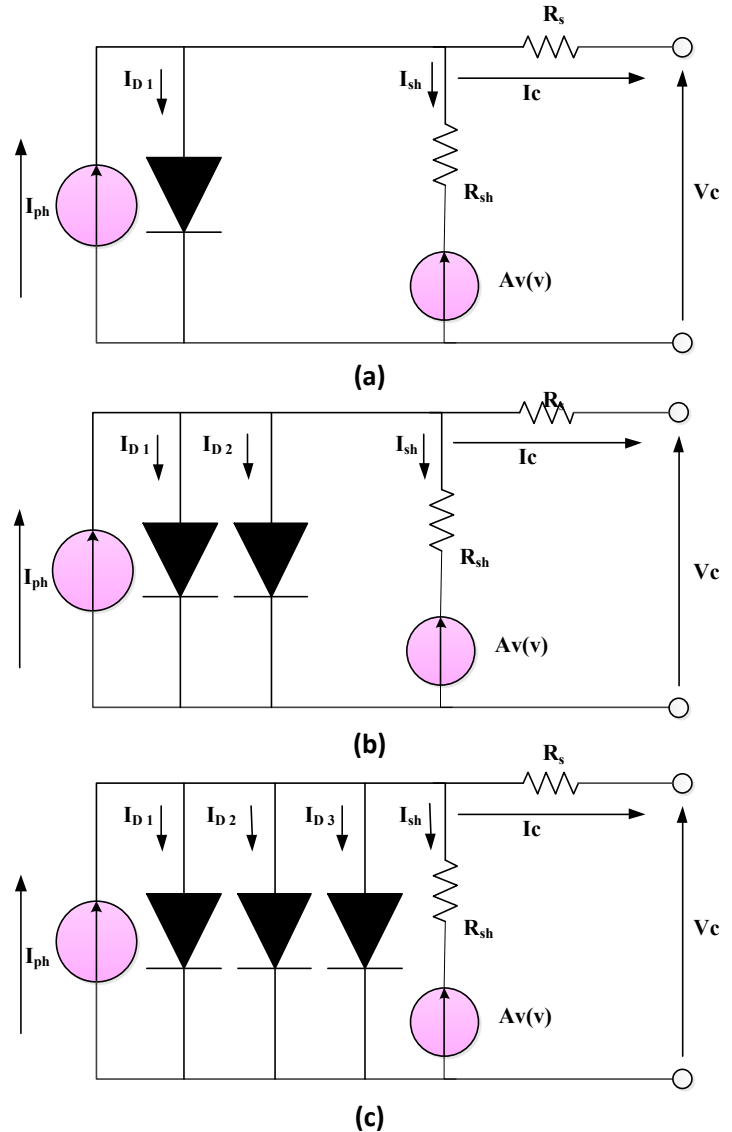


Fig. 3. MJSC model represented by (a) SD, (b) DD, and TD model.

3.3 Concentration Effect Analysis

Calculations were performed using an increase in concentration to examine the performance of various electrical parameters under varying SR and Cr . As shown in Figure 7, all electrical parameters increased with SR and Cr fluctuation.

Figure 7(a) demonstrates that V_{oc} increased logarithmically with SR at constant Cr and temperature, rising from 2.73V to 2.93V as SR increased from 200 to 1000 W/m². V_{oc} is defined by I_{sc} and I_O based on Equation 9. Both currents rose with increasing Cr , though I_{sc} increased more than I_O . Consequently, V_{oc} also increased as Cr rose. However, the rate of increase fell as Cr rose - for

example, the V_{oc} increase was smaller going from 3.00V to 3.17V at 500X Cr compared to 50X Cr.

I_{sc} followed a linear trend against SR and concentration changes as shown in Figure 7(b). Unlike V_{oc} , I_{sc} 's increasing rate remained almost constant - it rose from 0.13A to 0.67A at 50X Cr and from 2.67A to 13.6A at 1000X Cr. As both V_{oc} and I_{sc} increased with Cr, the maximum power point voltage and current also rose, boosting the peak power of the MJSC.

Figure 7(c) shows cell FF increased with SR and Cr up to 500X, but started decreasing at very high concentrations (1000X). The increase in V_{oc} , I_{sc} and FF with SR led to higher MJSC efficiency. However, the rate of efficiency gain fell as Cr increased, as shown in Figure 7(d) - the increase went from 0.9% to 0.7% to 0.4% as Cr rose from 50X to 500X to 1000X. After 1000X Cr, efficiency began dropping due to decreased FF and increased bandgap.

Figure 8(a) illustrates V_{oc} 's temperature dependence at different Cr values. V_{oc} decreased less rapidly with temperature at higher Cr levels - it fell from 2.93V to 2.45V at 50X Cr but only from 3.2V to 2.81V at 1000X Cr. Thus, at lower Cr, dV_{oc}/dT_c decreased more sharply than at higher Cr.

Table1: Parameters for TJSC InGaP/InGaAs/ Ge [36].

Symbol	InGaP	InGaAs	Ge
$E_g(eV)$ at 273 K	1.79	1.519	0.7437
$I_{sc}(mA)$	13.6	13.7	19
$K(A/^{\circ}K^4)$	1.833×10^{-8}	2.195×10^{-7}	19.187×10^{-6}
$\alpha(A/^{\circ}K)$	0.008	0.008	0.006
n	1.89	1.59	1.43
γ	1.81	1.86	1.44
$\alpha(eV/K)$	7.5×10^{-4}	5.405×10^{-4}	4.774×10^{-4}
$\beta(K)$	372	204	235
$R_s(\Omega)$	0.023	0.023	0.023
$R_{sh}(\Omega)$	1000	1000	1000
$w_s(m/s)$	5		
$A_c(cm^2)$	1x1		

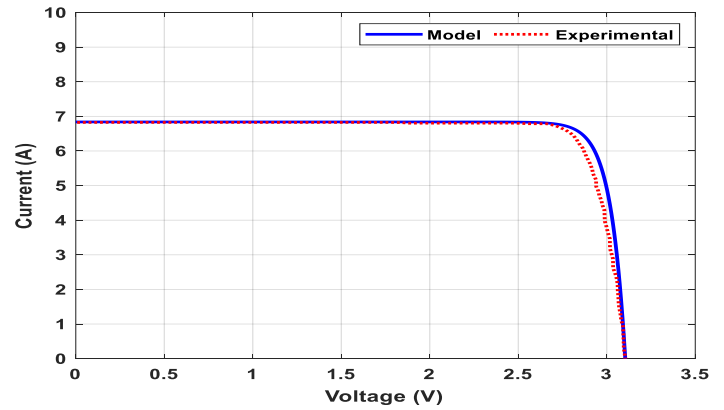
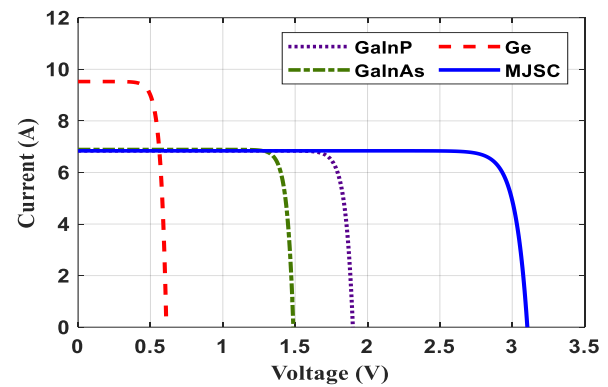
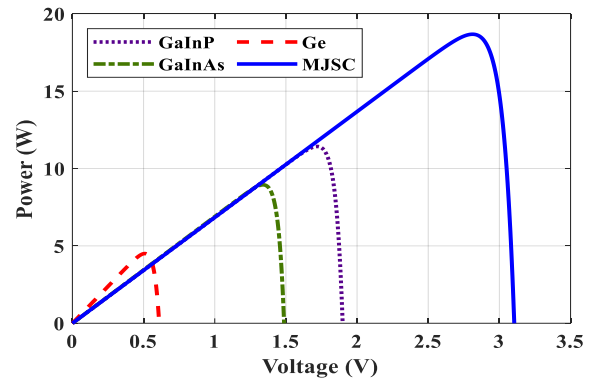


Fig. 4. I-V curves comparison for experimental data and proposed model.



(a)



(b)

Fig. 5. (a) I-V and (b) P-V curves of each cell in the TJSC and for the net cell.

Because of the energy bandgap being withdrawn at higher cell temperatures, more light photons are absorbed and free charge carriers are created. As a result, less energy is now required to discharge a free charge carrier [37]. That interpreted more current is generated (I_{sc}), fig.8 (b), with drop-in V_{oc} voltage, Fig.8 (a). At the same value of C_r , I_{sc} raised from 0.67A to 0.70A, from 6.71A to 7.01A, and from 13.51A to 14.11A. This value indicates that I_{sc} increasing rate with concentration level increment is fixed and proportional to C_r values. Because both V_{oc} and I_{sc} increased as C_r increased, the voltage and current for the maximum power point also increased, this occurs at higher

concentration only as voltage reduction rates is less than its values at low C_r values.

The influence of C_r on the FF of MJSC is presented in Fig.8 (c). The FF increase as the C_r values increased up till 500X it starts to decrease. That is because the increase in I_{sc} , V_{oc} , and P_{max} of MJSC, and the increase in the amplitude of I_{sc} was greater by comparison. The FF decreased with increasing the PV surface temperature due to the reduction in output power after 500X. For example, the values FF of the MJSC at surface temperatures of 25°C and 100°C are about 88% and 86% respectively.

From Fig.8 (d), for a direct SR value of 1000 W/m², it can be concluded that the efficiency was increased by increasing the. As C_r increased from 50X to 500X, and to 1000X, the efficiency value increased from 3.43% to 37.53% to 37.64% at 25°C cell temperature and from 33.52% to 35.14% to 35.41 at 100°C. it is observed that the temperature effect on MJSC efficiency decreases with concentration levels increase, 2.91%, 2.39%, and 2.23% efficiency reduction at 50X, 500X, and 1000X, respectively. The rates of electrical parameters changes with temperature increase at different concentration levels are indicated in table 2.

Table 2: MJSC electrical parameters temperature coefficients.

C_r	dV_{oc}/dT_c (mV/°C)	dI_{sc}/dT_c (mA/°C)	dFF/dT_c (%/°C)	$d\eta/dT_c$ (%/°C)
20X	-6.7	0.16	-0.0004	-0.0415
50X	-6.3	0.4	-0.0003	-0.0387
100X	-6.0	0.8	-0.0003	-0.0367
200X	-5.7	1.6	-0.0003	-0.0346
500X	-5.4	4	-0.0003	-0.0318
1000X	-5.2	8	-0.0003	-0.0297

Table 3 indicates the superiority of the proposed model over other models as it:

1. Not only covers all parameters that can affect the output of MJSC but also with a wider range of temperature, C_r , and SR.
2. Avalanche mechanism caused by breakdown or shadow is included
3. More practical model representation by DDM and TDM.
4. All temperature coefficients are calculated that can help in future research.

4. Conclusion

This work models a lattice mismatched TJSC consisting of GaInP/GaInAs/Ge with band gap energies of 1.79/1.519/0.7437 eV, respectively, using MATLAB. The model is based on the SD, DD and TD equivalent circuit cell models. An additional term modeling reverse bias, partial shading, and junction mismatch effects called avalanche breakdown voltage was incorporated. I-V characteristics were simulated to obtain the electrical parameters of this MJSC under varying conditions. SR levels from 200W/m² to 1000W/m², C_r values from 20X to 1000X, and temperatures from 15°C to 100°C were studied. Previous analysis found significant parameter changes only at higher concentrations, while lower concentrations did not justify high fabrication costs. Therefore, analysis focused on 500X and 1000X concentrations. The model predicted efficiencies of 37.53% at 500X and 37.93% at 1000X, approaching the world record of 47.1% for a 6 junction cell. While crystalline silicon heterojunction cells reached 25.6% efficiency, this MJSC design shows promise for higher efficiency. Temperature coefficients were determined to be -5.4V/°C for V_{oc} , 4mA/°C for I_{sc} , and -0.032%/°C for efficiency at 500X. At 1000X, coefficients were -5.2V/°C for V_{oc} , 8mA/°C for I_{sc} , and -0.029%/°C for efficiency. In summary, the model effectively simulated the electrical performance of this lattice mismatched TJSC cell design under varied operating conditions.

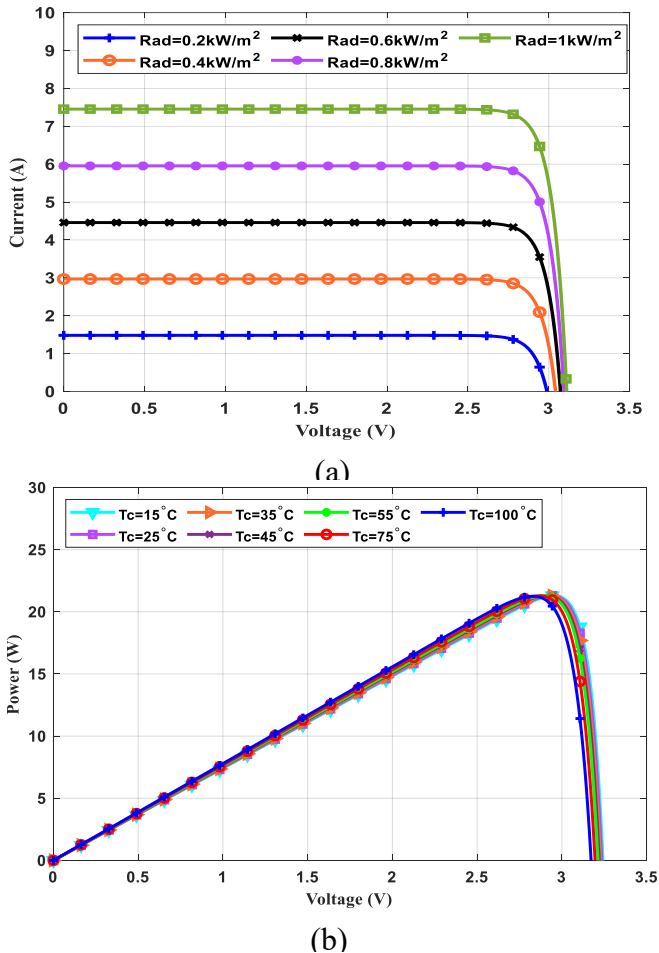


Fig. 6. (a) Effect of SR increment on MJSC I-V characteristics, (b) Effect of temperature increment on MJSC P-V characteristics.

Table 3: Comparison between the proposed model and previous approaches.

Ref	Model type	Bishop	Input variables			Output Coeff.
			Temperature °C	Cr Sun	SR W/m ²	
Wang [2]	• SDM	×	25-60	×	×	
Fernández [13]	• SDM	×	0-100	×	×	-
Catelani [17]	• SDM • DDM	×	×	150-500	×	-
Sharma[18]	• SDM • DDM	×	25,100	×	600,1000	-
Burhan[21]	• SDM	×	25-90	50-500	×	$dVoc/dTc$ $dIsc/dTc$
Hussain [38]	• SDM	×	30,100	×	500,1000	-
Smith [39]	• SDM	×	31-87	×	400-1000	$dVoc/dTc$ $dIsc/dTc$ dFF/dTc d_{eff}/dTc
Khatibi [40]	• SDM	✓	×	×	500-1000	$dVoc/dTc$
Domínguez [41]	• SDM	×	25-75	100X-700X	×	-
This work	• SDM • DDM • TDM	✓	15-100	20-1000	200-1000	$dVoc/dTc$ $dIsc/dTc$ dFF/dTc d_{eff}/dTc

Conflict of Interest

Acknowledgements

N/A

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

All authors were responsible for the conceptualization, validation, resources, data curation, software development, and project administration. They jointly contributed to the methodology, formal analysis, investigation, original draft preparation, review and editing, visualization, supervision, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Research Data Policy and Data Availability

All data generated are included in the paper.

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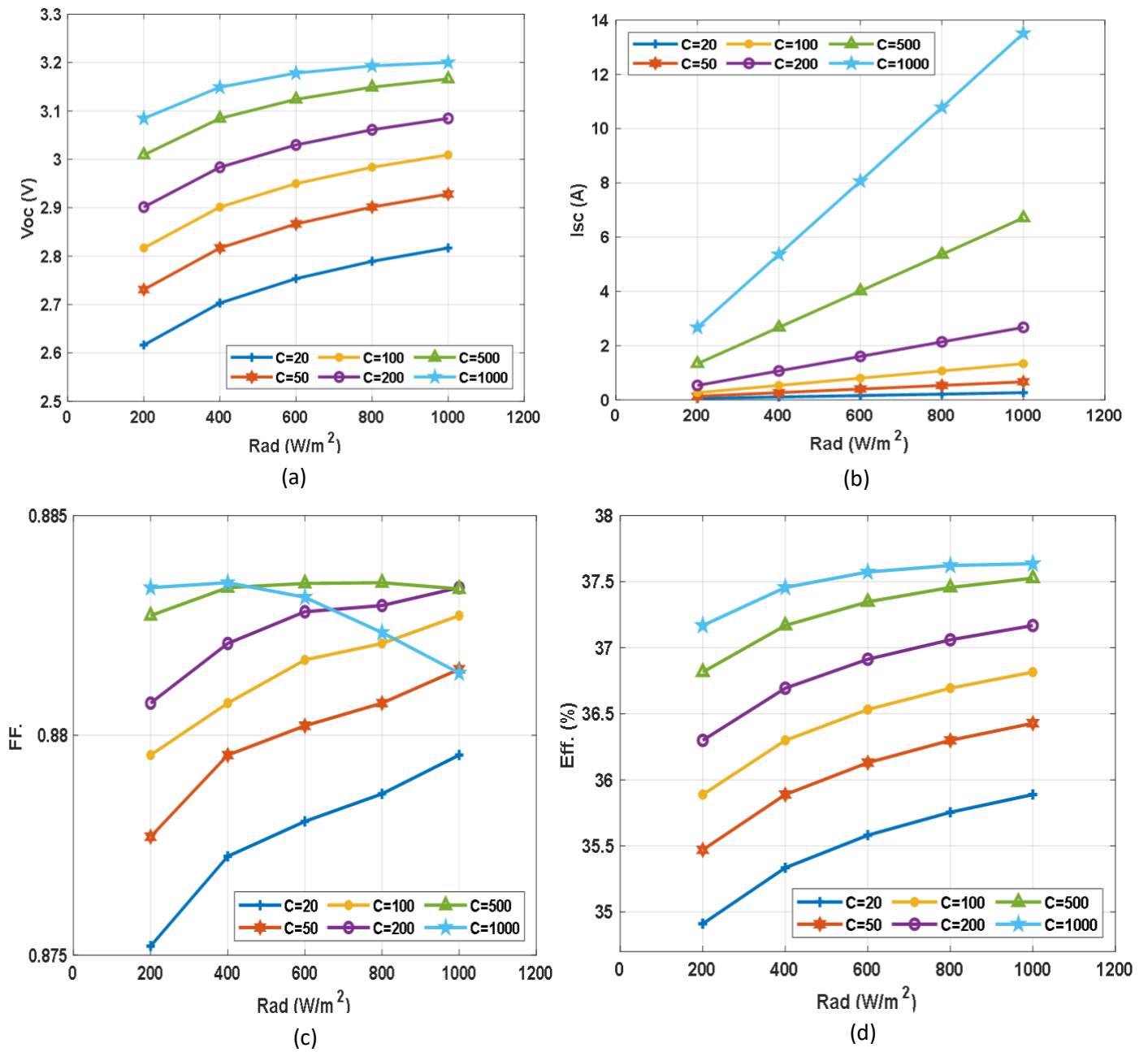


Fig. 7. Effect of SR increment on cell (a) V_{oc} , (b) I_{sc} , (c) FF , and (d) Efficiency with C_r variation.

Fig. 8. Effect of C_r on cell (a) V_{oc} , (b) I_{sc} , (c) FF , and (d) Efficiency with temperature variation.

